THE WHIRLIGIG OF TIME: SOME THOUGHTS ON STADDON AND HIGA

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Staddon and Higa's theory of timing finds analogy with physics' concern with the relativity of time and irreversible processes. Their model raises general issues about the nature and function of models and, specifically, the extent to which it has captured the stimulus events in temporal control.
Key words: memory, models, relativity, timing

> The time is out of joint. O cursed sprite,
> That ever I was born to set it right!

Hamlet's lament may echo many of those researchers who have taken up the task of understanding the nature of time itself. Time as an entity of scientific concern has largely been the province of physics, where time stands as one of the four fundamental dimensions along with length, mass, and charge, whose combinations define virtually all other physical variables. Yet, time remains the most mysterious and contentious of the set. Two major issues have vexed the physicist. Both were raised by Newton who asserted the absolute quality of time, and, moreover, in creating "a system of the world," founded a physics where time had no direction. The absoluteness of time was challenged and resolved by Einstein, who showed that measures of time were dependent on states of motion. The second, that of understanding nature's ubiquitous irreversible processes in the face of a temporally reversible mechanics, is still a hotly debated issue (e.g., Coveney & Highfield, 1990; Davies, 1995; Price, 1996). The relativity of time and temporal irreversibility are both touched by the contributions of behavior analysts and others to the psychophysics of temporal control. Staddon and Higa's article reflects this in ways I will try to point out.

The relationship of psychophysics to relativity theory is only metaphorical but I think conceptually useful. Let us confine ourselves to special relativity for the sake of simplicity, although that is not a requirement. Special relativity is founded on only two postulates: (a) The speed of light is a constant independent of the uniform motion of the observer, and (b) the laws of physics hold independently of the uniform motion of the observer (general relativity extended these postulates to nonuniform motion). From these two postulates, the Lorenz transformation can be derived, which yields values of fundamental units of length, mass, and time for observers moving relative to each other. For example, the time t' in one inertial frame, K', can be determined from another K, at any time t, by a multiplicative factor that depends on the relative velocity of the frames. The scale with velocity is essentially hyperbolic. A key point here is that there is no privileged frame. Assuming each has a proper clock, both have the correct time relative to their frame of reference, and there is no "true" time outside to serve as an absolute standard. The same, of course, is true of the other fundamental measures.

Psychophysics and extensions into the general domain of temporal discrimination and differentiation deal with the question of what transformation rules apply to carry us from the experimenter's frame to the subject's frame and back. Another way of looking at this question is how does the subject scale the variables thrown at it by the experimenter. Although experimenters may think they have a privileged frame, they do not; they simply have another scale, and often a crude one at that. The term *psychophysics* has implied to some the description of a field devoted to understanding the relationships between the "physical" world and a "mental" world, and thus is reflective of a dualist position even if unintended. But all we are concerned with

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here is physical in the sense that the organisms we study are as physical as the clocks we study them with. Moreover, perhaps by determining the transformation rules between one mechanism and another, we might understand how each works. In the typical experimental arrangement, we take for granted one scale or mechanism, say, a laboratory clock, and use it as a calibrated gauge to study the scaling and possible mechanism of our experimental subject.

Now, one may assume that because we use and understand the mechanism of our gauge or standard, the experimental organism possesses a similar gauge that it then uses to transform our imposed values into its own. In other words, if we impose a temporal contingency, discrimination or differentiation, upon an organism, it must then consult its own clock and report back its readings to us. Thus begins the search for the internal clock. It is easy to see why the notion of an internal clock is so seductive. The construct is a sort of copy theory in the same way we might attempt to understand how we see by putting a picture of the world in the head that we then look at from the inside. Similarly, to understand how the behavior of an organism might come under control of a putative temporal contingency, theories like those of Church and Gibbon (e. g., Church, 1989) endow the creature with an internal clock. The research program is then devoted to understanding the properties of this clock. With this commitment, the clock must require a host of other constructs to make it work: a gate, an accumulator, and an interplay between a reference memory and a working memory system through a comparator. Despite this rococo structure, we are still unable to determine how the clock or any of the other constructs are activated or controlled. How is the clock read? How does this system instigate behavior? One might build a program or device with all these features, including the missing functions, but this kind of model has no particular biological reference or significance. More significantly, as Staddon and Higa argue masterfully, the model does not consistently work. All the Ptolemaic epicyclic fiddling to make the model fit only diminishes its credibility.

In the absence of this fiddling, the model does not generate the proper transformation rules. Analogous with relativity theory, what these rules are depends on the contingencies imposed and the contexts in which they operate, as Zeiler (in press) has emphasized. This is not surprising. For example, in temporal differentiation, one tries by various procedures to make the organism into a clock; in temporal discrimination, one tries by various procedures to see how good a clock the organism can be. Is it any wonder the scaling is not comparable? Adding more and more internal clocks to account for the varieties of findings is clearly not a satisfactory strategy.

An internal clock is not per se implausible. There is substantial evidence for several such clocks to help account for various infradian, circadian, and ultradian cycles. The clocks themselves appear to result from dynamic limit cycles in protein synthesis that, in turn, control neural or hormonal activity. At least some of these clocks may be entrained by external stimulation (*zeitgebers*), showing that different rhythms or phases of the same clock may be generated depending on the environment. A shift in sleep time with significant changes in time zones is a familiar example. Those who advocate an internal clock to account for the effects of a temporal contingency could view such a contingency as a kind of zeitgeber that entrains behavior to conform more or less to the ongoing requirements. One metaphor is resonance as we tune a capacitor in a radio LC circuit to receive a desired frequency. Another metaphor is a coupled pendulum system wherein the motion of one pendulum entrains the motion of another. How useful such metaphors might be for developing models of timing remains to be seen.

Staddon and Higa provide a model based on an RC circuit called an integrator (also known as a low-pass filter). Equivalent circuits in neurons and synaptic junctions control neural integration. As the name implies, inputs to such a circuit are integrated via a charging capacitor. The output depends on the shape and frequency of the input signal and on the time constant of the capacitor. These devices may be cascaded using capacitors with different time constants to yield the sort of properties Staddon and Higa require to conform to some available data. This technique is, of course, another kind of fiddling to make things fit. If the data do not fit with

n such units, then make it $n + 1$. This, of course, piles parameter upon parameter. At least, Staddon and Higa might argue, their model only comprises one *kind* of device. This limits the model's applicability as they acknowledge. For example, the model cannot account for what surely is the most interesting property of performance under fixed-interval (FI) schedules—the temporal patterning. I would be curious how Staddon and Higa might approach the scale-invariant properties of fixed-interval patterning shown by Dews (1970), or his "Cheshire cat" phenomenon using multiple S^{Δ}s (Dews, 1962). There was also no treatment of interresponse-time (IRT) schedules, either properties of IRT distributions or the power law relations between IRT requirements and emitted IRTs (see, e.g., Zeiler, 1979). With schedules like IRT $> t$, reinforcers occur aperiodically, and thus a leaky integrative system like the one proposed would have to be modified to include a response memory. Also with IRT $> t$ and FI t, as well as many other contingencies, models will have to deal with variations in responding controlled or induced by the dynamic interplay between patterns of behavior and patterns of reinforcement.

The role of a memory system touches the topic of temporal irreversibility, the second contentious issue mentioned above in the attempts to understand the nature of time. Staddon and Higa do not waste much time, however, on the most salient manifestation of irreversibility, namely learning or acquisition, but rather assume all that has already taken place. The Staddon and Higa model is based on a "memory-as-stimulus" principle; in other words, salient events produce a temporary state in the organism that varies with time. Values of that state constitute a stimulus that controls when responding will occur. Conceptually, this sort of model suffers from the same problems encountered by its alternatives, namely how do states, traces, counts, and so forth, become behavior? Perhaps the question is not quite fair, because we rarely have the answer to this question regarding any physiological process. Nevertheless, in this model, there is no particular push for physiological plausibility. The issue here is whether an analytical account requires a commitment to any particular picture, for example, a fantasy physiology. Indeed, the advantage of a mathematical account is that, once developed, it may be relatively free of pictures. Maxwell's equations, once formulated, no longer depended on Faraday's lines of force or Maxwell's own hydrodynamical ether machine (see, e.g., Marr, 1993). What is essential to a successful model is a pattern of functional relations that properly encompasses the measurable variables of interest. A picture may be but a heuristic crutch, and a dangerous one at that. Such pictures are all too often taken literally.

I mentioned earlier the possibility of building a device as proposed in the Church and Gibbon account. So one might with the Staddon and Higa model. This reflects the engineering aspect of modeling; that is, the model may be instantiated in an actual device that displays the needed properties. The model itself is, of course, derived from known properties of such devices. Many different models may be analytically equivalent, so in the absence of understanding the real organism, perhaps one should be free to use any device that works. But such an approach could not be considered organism based, in the sense that Staddon has advocated in earlier papers (Marr, 1993; Staddon, 1993, 1997).

I am unclear as to the nature of the stimulus that controls behavior in the Staddon and Higa model. Indeed, the long history of the behavior analysis of timing has not provided much enlightenment on this issue, regardless of theory. Catania (1970), in his classic paper on timing, asserted that "Duration, like frequency, intensity, or spatial extent, is a discriminable property of stimuli" (p. 36). But what sort of feature is duration? And what of time itself? If the only property of time is that it has duration, then this leads us to the pointless conclusion that the only property of time is time. Years ago, the philosopher Jack Smart argued the illusory character of the "temporal stream." How fast does it flow? Presumably one second per second! Moreover, as the physicist David Park shows, it is impossible to perform an experiment demonstrating the passage of time (for a discussion of these points, see Davies, 1995). Relativity teaches us that we dwell in a space–time continuum; time no more flows than does length. Time can only be keyed by events. In Emily Dickinson's words, "Forever—is composed of Nows." Less elegantly, time is just one damn thing after another. Control via time is control by events, including behavior itself. A clock is a generator ("tick-tock") or marker ("October") of events. Both the Church–Gibbon and Staddon–Higa theories acknowledge the equivalence of timing and counting. What remains perplexing and elusive are those events that control the sorts of behaviors Staddon and Higa and all the other clever researchers in this domain have attempted to capture. The rest of us may exclaim in Viola's words from *Twelfth Night*:

O Time, thou must untangle this, not I;
It is too hard a knot for me t' untie!

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TOLERANCE IN A RIGOROUS SCIENCE

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Scientists often evaluate other people's theories by the same standards they apply to their own work; it is as though scientists may believe that these criteria are independent of their own personal priorities and standards. As a result of this probably implicit belief, they sometimes may make less useful judgments than they otherwise might if they were able and willing to evaluate a specific theory at least partly in terms of the standards appropriate to that theory. Journal editors can play an especially constructive role in managing this diversity of standards and opinion.

Key words: tolerance, diversity, truth, conviction, parsimony, historicity

Staddon and Higa's paper is one of most stimulating and provocative I have read for some time in the literature on timing. I hugely enjoyed reading it, and I strongly supported its publication. I did not do this because the theory seems true, because it addresses core timing data that I believe any theory of timing must address, because it best satisfies a law of parsimony, and especially, I did not support publication because reading the paper con-

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